# Mechanical Design Concept for TASD

We present a self consistent conceptual mechanical design for the TASD structure.

Based on the results a number of FEA studies of component problems.

Supported by many people, principally Ang Lee with a huge amount of FEA calculations, and a number of people (Vic Guarino, Jim Grudzinski, John Cooper and many others) challenging and validating the design.

# Structure of this Talk

Introduction and Problem Definition

Description of the complete detector

How much Stress should be Allowed in PVC

Single oil filled vertical extrusion

Failure Modes of Large Assemblies

Stress buildup at the bottom

A Stability Concern--cataclysmic progressive failure

Are we safe?  FEA results

# Structure of this Talk-cont'd

A Coherent Design

Start with one Bookend

Assembling the Detector from Blocks

Gluing the Tops of Blocks together

Assembling a TASD

The Block Raiser

What is the Right Block Length

# Introduction and Problem Definition

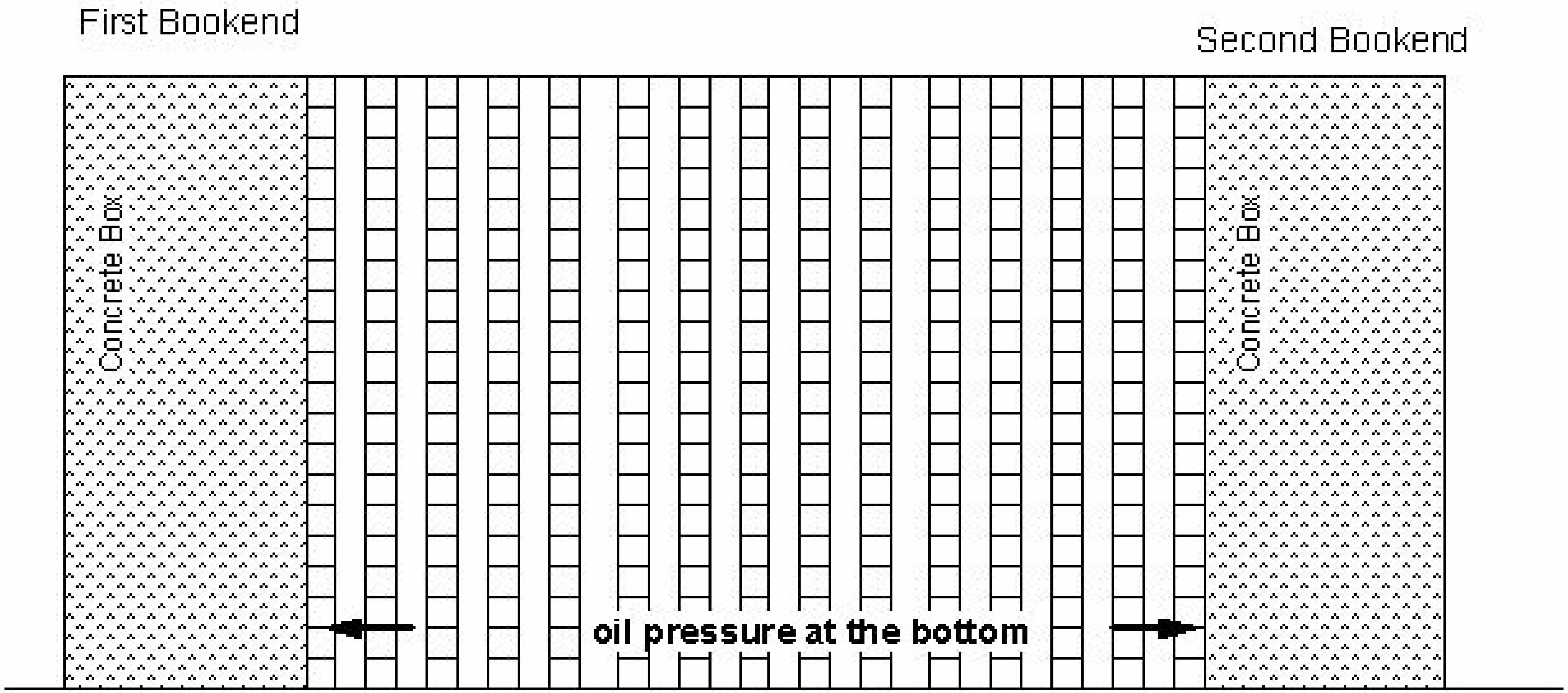
This talk addresses mechanical structural issues

The Totally Active Scintillation Detector (TASD) is an unusual structure because of the size and choice of material (PVC). It has 1845 planes made up of 34 extrusions, each having 32 cells.

We must identify and address all potential failure modes.

TASD is required to operate completed parts of the detector while the remainder is being built.

# The Ideal Detector




The oil pressure exerts a force of 5.14 million pounds on each bookend.
The bookends can be designed to take it,
but a partial detector assembly without bookends cannot.

**Complete Detector, idealized**

# The Real Detector

The fluid pressure forces must be contained other than through bookends

Instead, the forces will be contained by the strength of individual cell walls of an extrusion.

We will show how this can be done.

(Note also that, with hard bookends, thermal expansion for a 10 C rise would put cell webs into 400 psi compression, leading to buckling collapse)

# How Much Stress should be Allowed in PVC

There are many grades of PVC (Vic Guarino summary)

PVC Pipe Classifications
A classification system based on hoop stress that causes failure of the pipe at 1000,000 hours (11.43 years).

| Designation | Design Stress |
|---|---|
| PVC1120 | 2000psi |
| PVC1220 | 2000psi |
| PVC2120 | 2000psi |
| PVC2116 | 1600psi |
| PVC2112 | 1250psi |
| PVC2110 | 1000psi |

# PVC Stress, continued

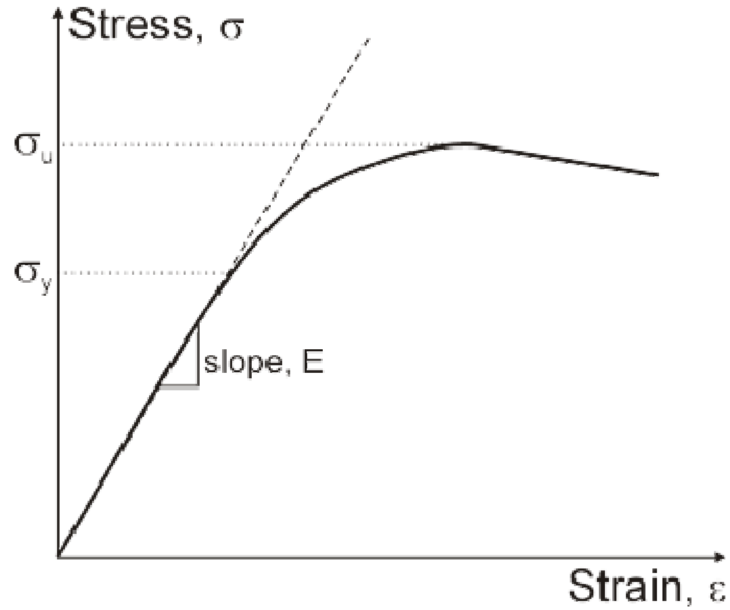
Failure is in creep (followed by pipe buckling).
The allowable stress depends on the stress pattern.

For NOVA, the consequences of failure are more severe than for sewer pipe.
On the other hand, our FEA's show the high stress points to be very small and isolated. If creep occurs, it will re-distribute the forces over a larger area, relaxing the stresses without a failure occurring.

We use a maximum acceptable stress of 1000 psi
No additional safety factors are used.

# PVC Stress/ Strain, measured

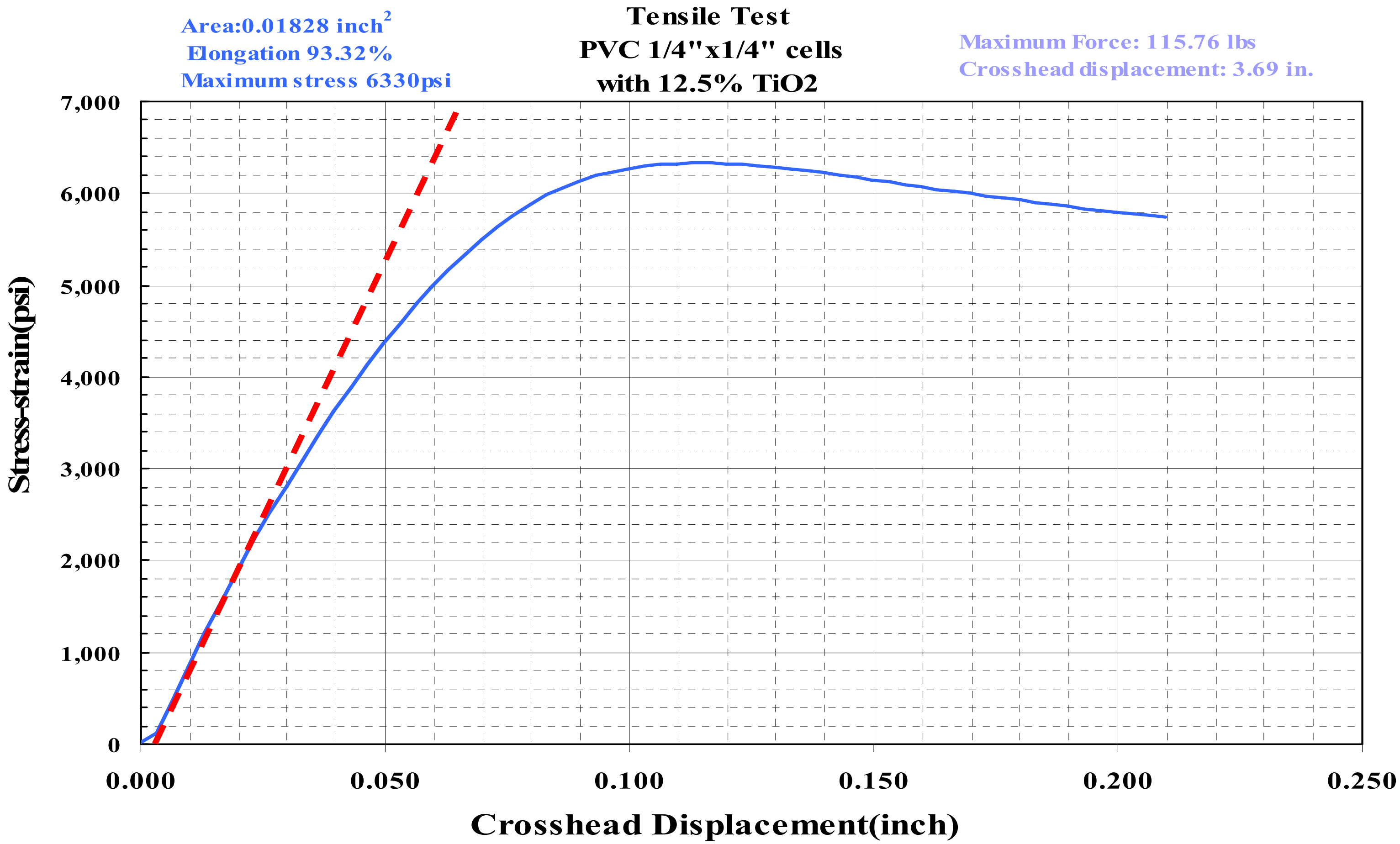
Unlike metals (picture at right), PVC has no clear-cut elastic limit.
The stress / strain curve starts out rather straight ( elastic modulus of 313 ksi) and curves over, beyond 2 ks, well before reaching its maximum stress. The rounding over depends in part on the speed of testing.




Creep is a steep function of stress and is negligible at 2 ksi.

# PVC Stress/ Strain Data

We have measured the yield stress in the kind of TiO2 loaded PVC that we expect to use, at around 6 ksi.



# Finite Element Analysis Work

This talk is based on a significant amount of study and of design work and finite element analysis (FEA).

Simulations ranging from single cells to assemblies of 40 planes have been carried out (Ang Lee).

We will present results in the same order, small to large.

We think we understand the PVC structure.

# Oil-filled Vertical Extrusion

Hydrostatic pressure at the bottom of vertical extrusions is 21 psi.

The pressure creates a down force on the bottom closure plate which represents the full weight of the oil;

The pressure tries to bow out the outer walls

It stretches the webs between adjacent cells.

# Summary of FEA Results for 3 mm side walls and 2 mm ribs

If horizontal planes are glued to the vertical planes, the highest stress is 502 psi. It increases to 1128 psi (barely acceptable) if only 30% of the area is glued.

| | Vertical and Horizontal extrusions Fully Glued | 30% area glued |
|---|---|---|
| Deflection | 1.2 mil | 2.2 mil |
| Max stress | 502 psi | 1,128 psi |
| Max shear in the mid plane | 75 psi | 245 psi |

# FEA Results: Strain for glued cell

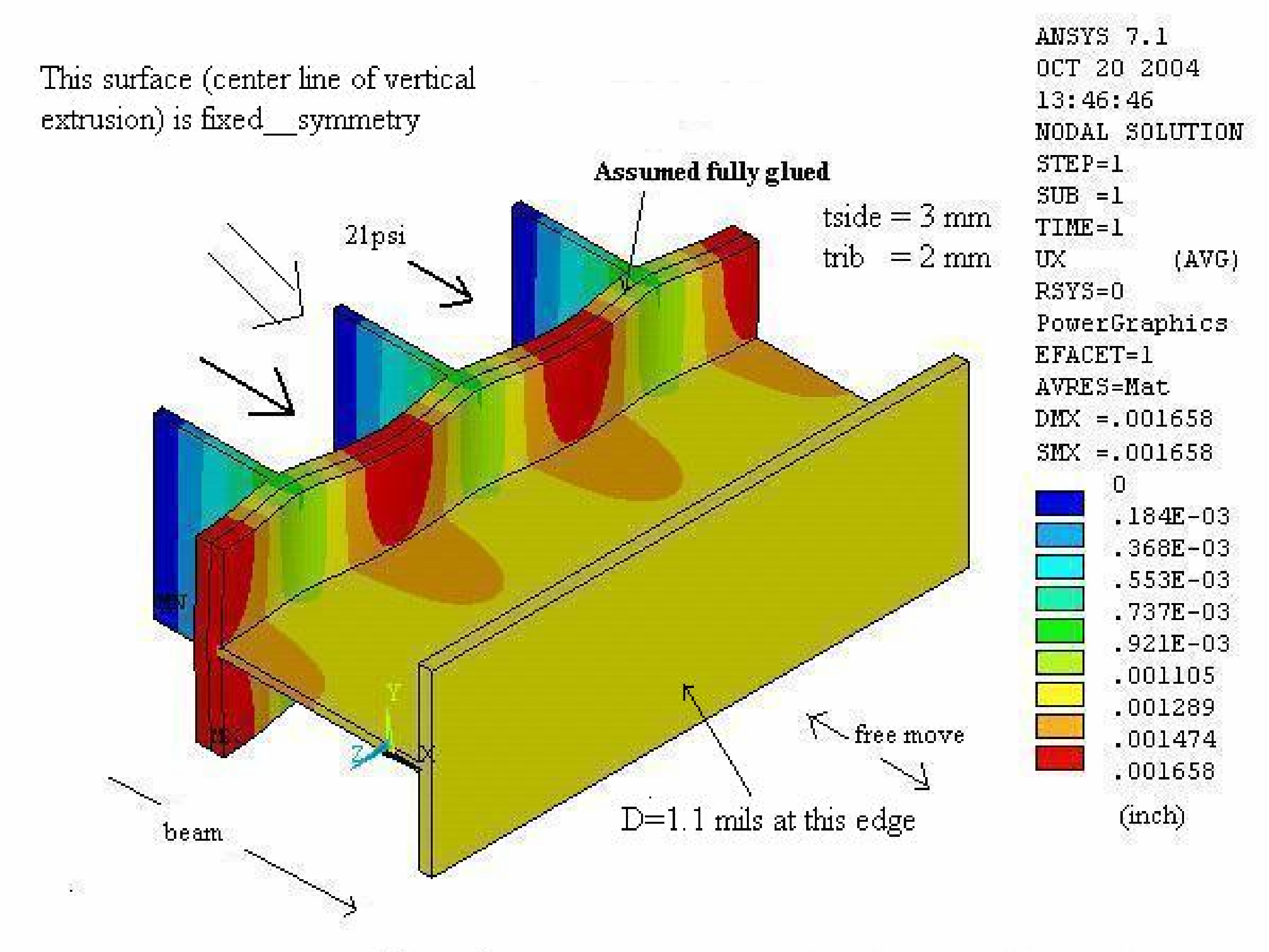



Figure 1 **Deflection along the beam direction for a fully glued case**

# FEA Results: Stress for glued cell

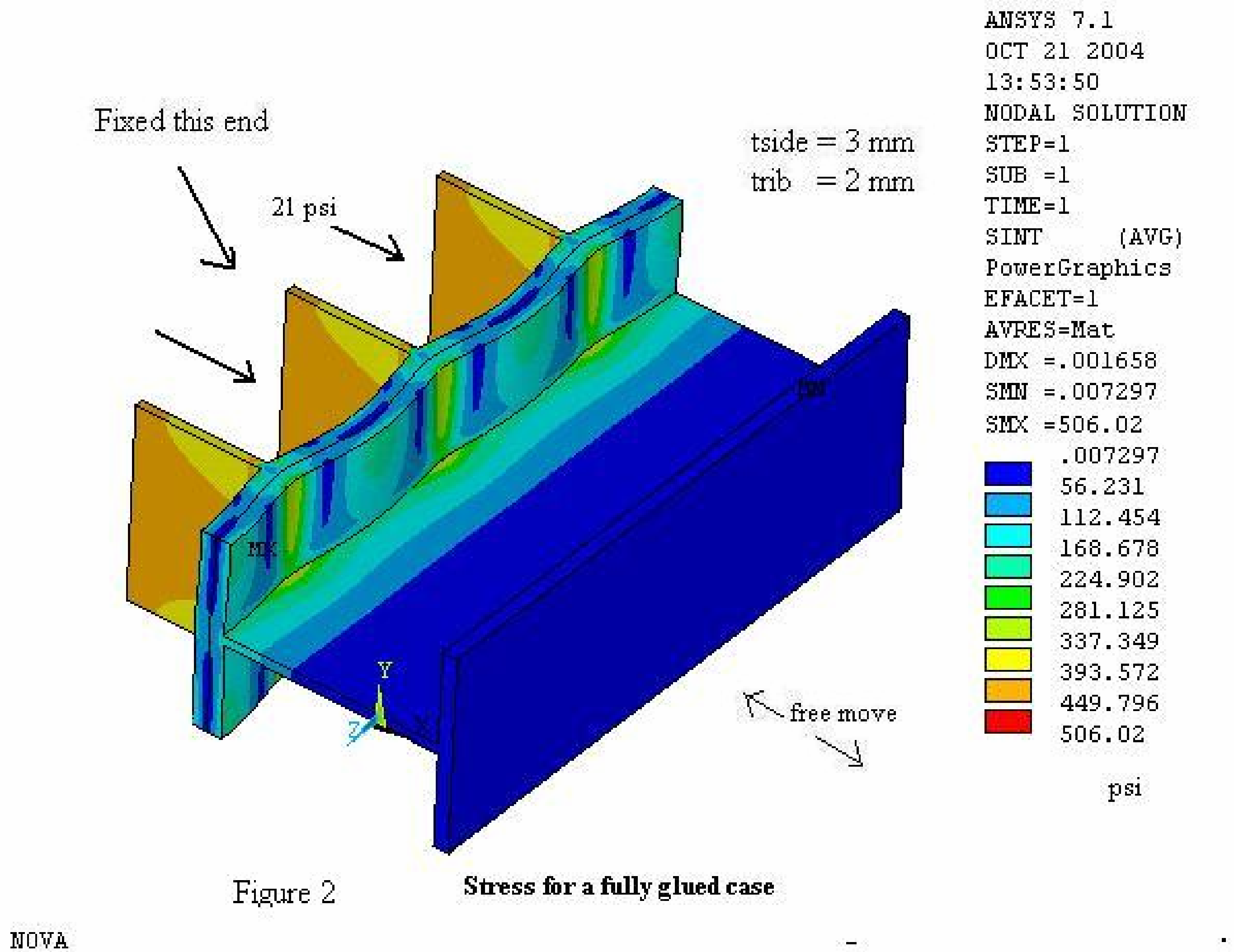



Figure 2 **Stress for a fully glued case**

# FEA Results:
# Strain for partially glued cell

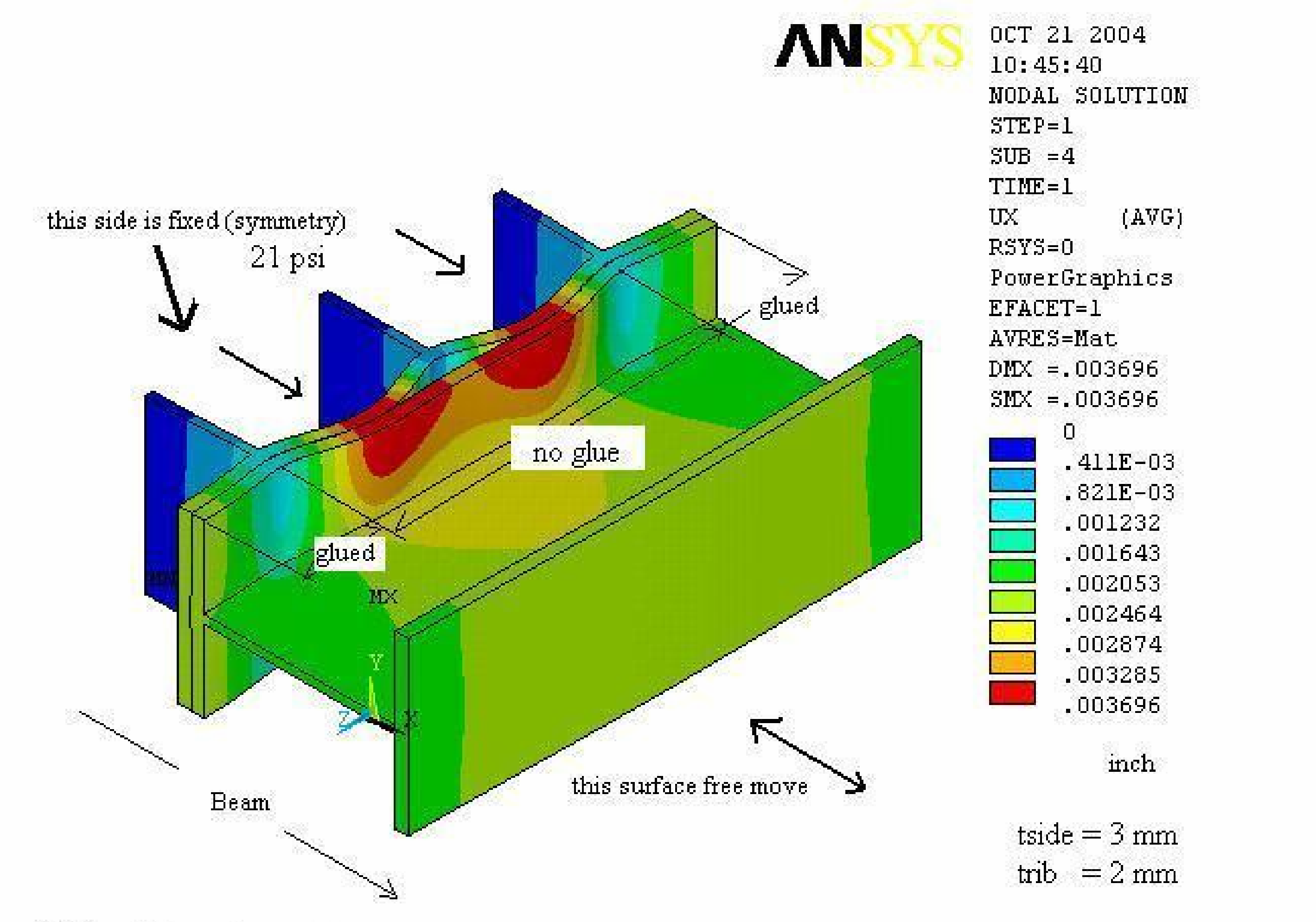
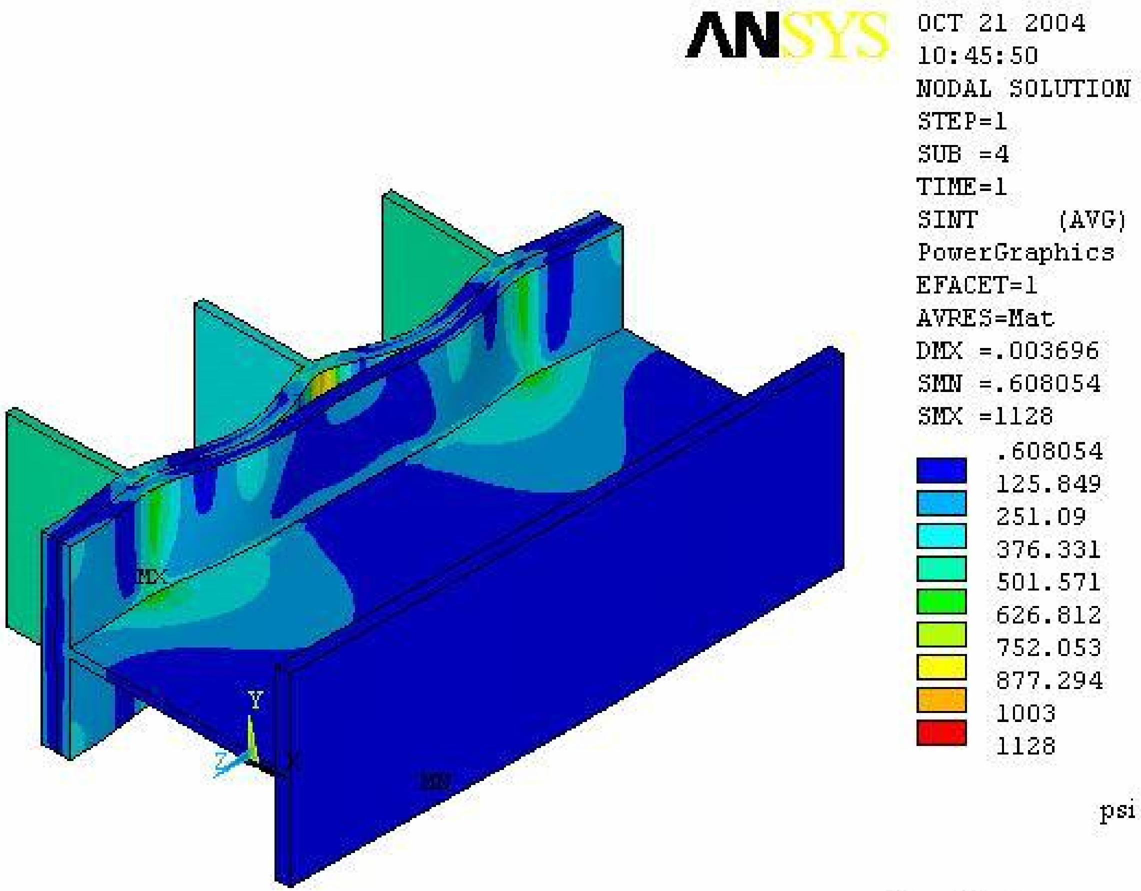



Figure 4 **Deflection along the beam direction for a partially glued case**

# FEA Results:
# Stress for partially glued cell




tside = 3 mm
trib = 2 mm

Figure 5 **Stress for a partially glued case**

NOVA

# What if an Interior Web fails?

The supported span becomes twice as large (an “aneurysm” failure).

Do we still meet the stress limit? The adjacent layer webs will help, assuming the glue bond is good between layers.

**However, if one web fails, it is quite possible that one has a bad extrusion, and other webs will also be weak.**

It will be necessary to test all incoming extrusion blanks at high pressure. This test is repeated once the ends are installed.

**If a whole extrusion drains ?**
No Problem.  Extrusions easily support external pressure.
All horizontal extrusions must do this anyway.

# Oil Filled Horizontal Extrusions

the oil volumina of the horizontal extrusions are separate from one another, and referenced to the atmosphere at each extrusion snout separately. This keeps the hydrostatic pressure small, about 1.5 psi.

Individual cells are capable of supporting the load of all horizontal oil filled extrusions above them. However, extrusions with many cells buckle under small loads.

The Horizontal Extrusions must be glued to the Adjacent Vertical Extrusions to transfer their weight into the vertical extrusions and to resist buckling.

# Failure Modes of Large Assemblies

## Stress build up at the Bottom

The Vertical Extrusions will swell
by about 0.002" in beam direction, at the bottom where the pressure is highest, due to bowing out and due to stretching of the webs.

They will stretch about twice as much when the glue covers only 30 % of the contact area to horizontal extrusions.

They will not bow or stretch out at all at the top.

We will examine how this affects a stack of planes.

# Will the Planes Slide under the Pressure Forces?

Vertical extrusions exert a weight pressure of 21 psi to the ground. When adding the weight of the horizontal extrusions, this is doubled; on average the force for each plane is about 30,000 pounds per plane.

The pressure force from the oil in beam direction should be strong enough to simply push the extrusions out of the way.

We have, however done an FEA analysis on a 40-plane stack of planes, and find that only the lowest 2 inches or so exert a horizontal pushing force on their base plates, in beam direction

Above that the PVC deforms and does not transmit forces to the base plate.

# The Effect of Friction Force for a 40 Plane Block

A very large FEA model simulates a realistic detector construction sequence.

In the model, 40 dry PVC planes are placed in their final location, glued together .

The 40 plane model starts filling its first 4 extrusions, and a solution is obtained.

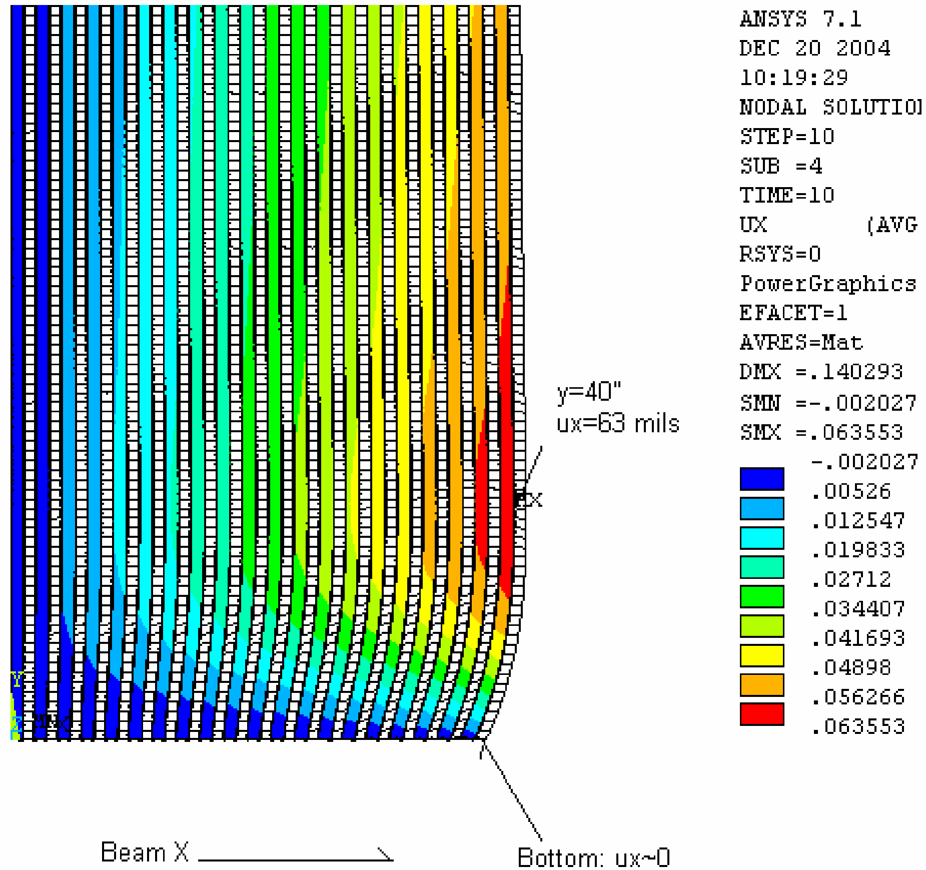
Next, another 4 extrusions are filled into a previously deformed geometry and second calculation is performed and so on.

The friction coefficient is assumed to be 0.3 cross the bottom.

# The shape of planes

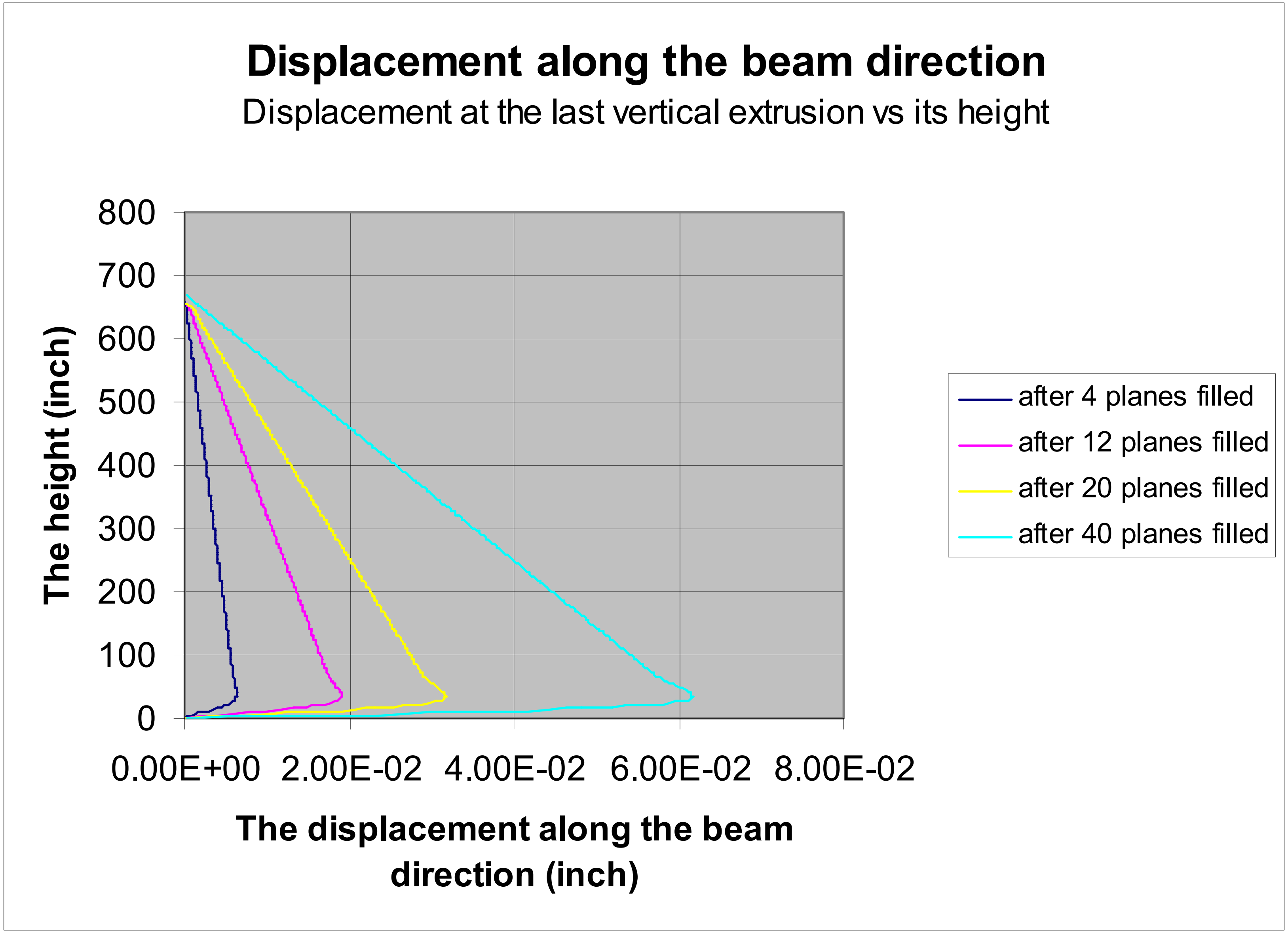
(Picture only shows
Bottom 10 ft out of 55 ft)

Clearly the extrusion bottom plates have moved very little while the extrusions above 3 ft from the floor have simply moved downstream in response to the swelling.




Displacement along X direction for the case of the 40 planes filled

# The Displacement in Beam Direction



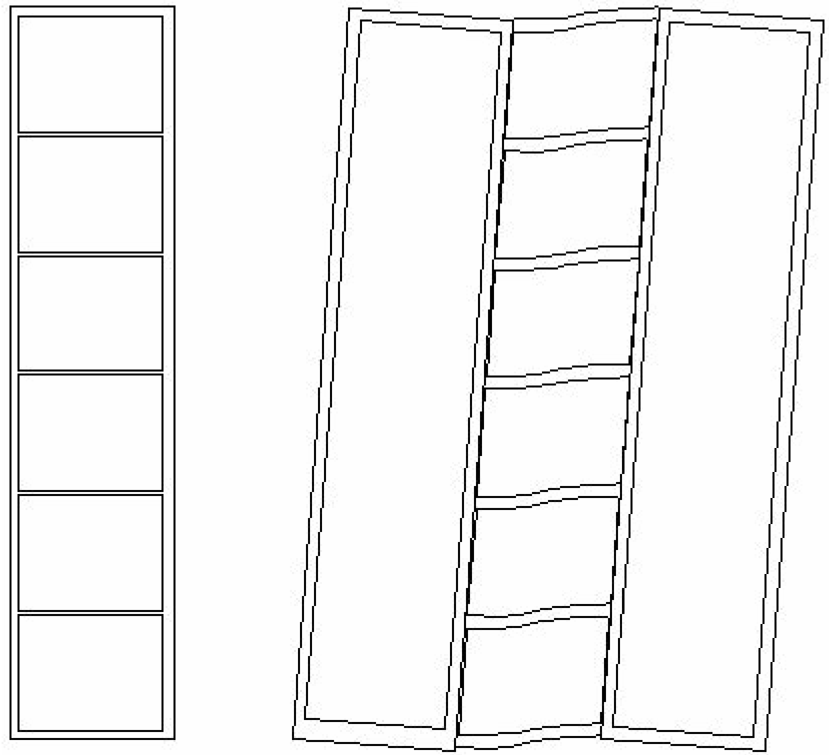
# A Stability Concern

A block of planes will deform when pushed horizontally in beam direction at the top.

As the extrusions lean, their weight is now off-center, and creates a horizontal force component that further increases the leaning.

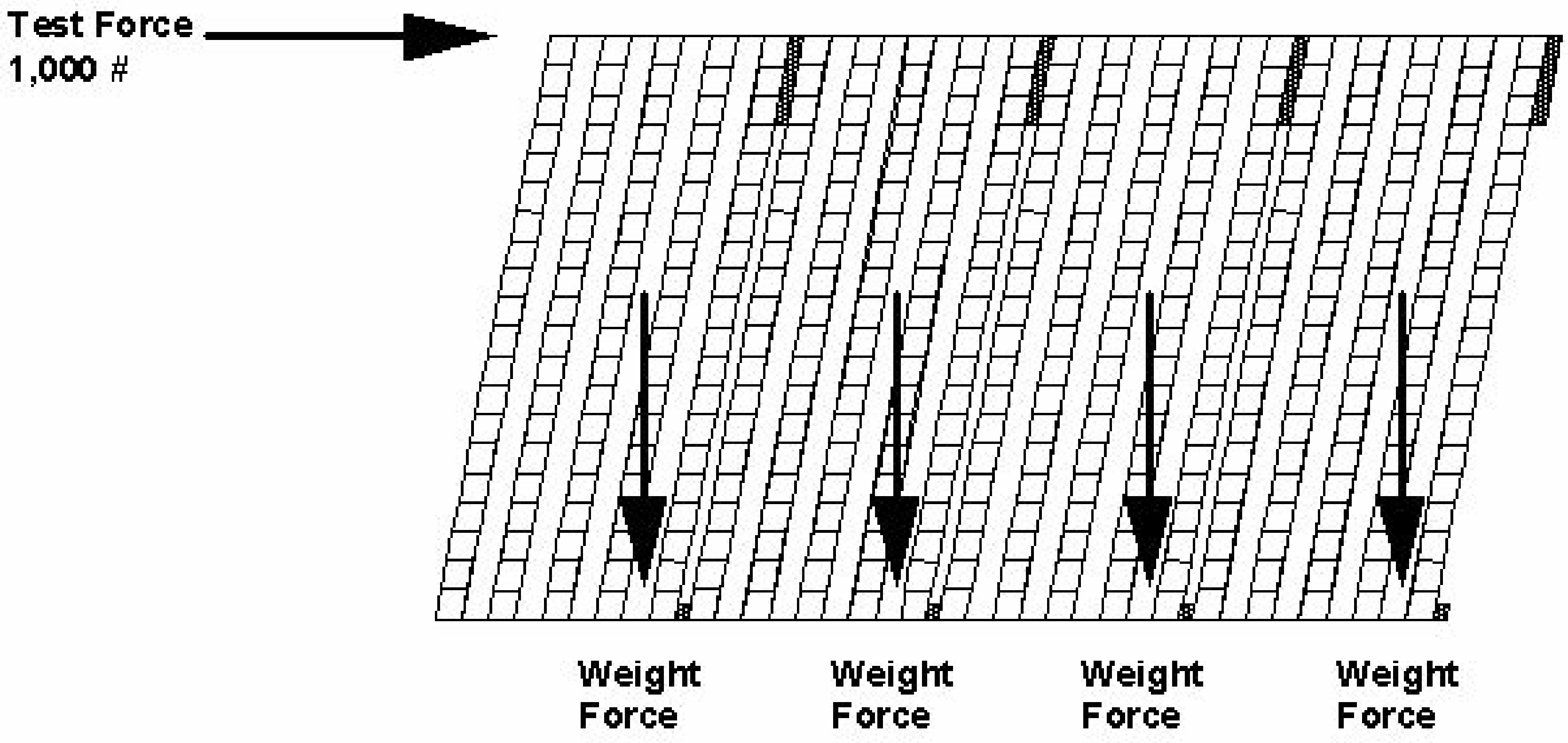
This is a classic stability problem.

The deformation looks like this:



Horizontal extrusion undergoing shear deformation

# Stability: FEA Results




**Stack Collective Stability Test**
20 plane block: 0.95 inch top move without mass force; 1.68 inch top move with mass forces
40 plane stack: 0.25 inch move without mass forces; 0.35 inch top movement with mass forces
(Stiffness goes with square of block length, approximately)

Buckling Safety Factor: 40 planes 3.4 20 planes 2.3

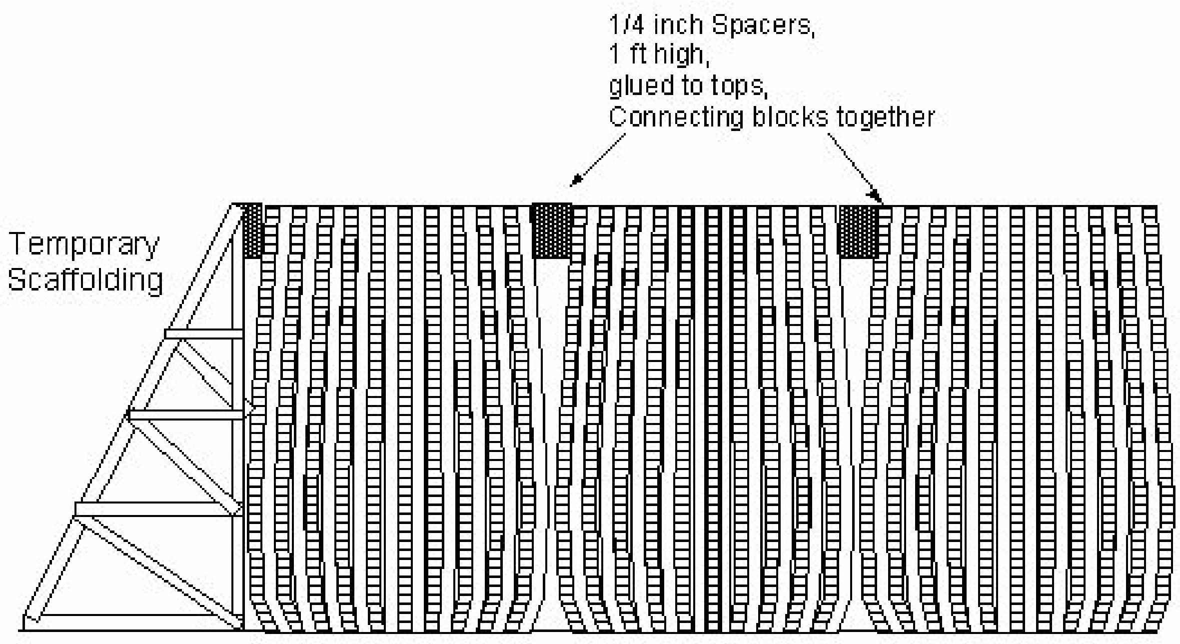
# Block Stability and Construction Safety

The buckling stability analysis does not address the tipping safety of a block.
If we take the rule of having the center of gravity no more than 3 base lengths above the floor, we find that the minimum length of a 53 ft high block would be 8.8 ft, or 30 pairs of planes long.
However, the tipping stability is decreased by the positive feedback discussed above.
It also relies critically on a sound glue connection between planes.

We looked at pre-leaning all planes by a small angle, for safety, but find that the cumulative forces, even for a 10 mrad angle, build up to where they would crush the extrusions.

# A Coherent Design

*The design is characterized by:*
---Starting with one scaffolding-type bookend
---Assembling the detector in individual blocks
---Leaving room for expansion between blocks
---Gluing the tops of all blocks together, using a spacer board




**Complete Detector, real**
(spacer thickness and bowing exaggerated)

# *Assembling the Detector from Blocks*

Blocks and the gaps between them an important design ingredient.

Gaps provide room for the swelling of the cells due to oil pressure. (and thermal expansion)

# *Swelling Space*

Cells will swell about 4 mils near the bottom from oil pressure.

Swelling is cumulative for successive vertical planes. For instance , a stack of 40 planes will swell by 0.080 inches on each side if free standing. This is not a large movement, but it creates stresses near the bottom of the vertical cells.

The stresses will exceed our 1000 psi limit if too many planes are added.

Small gaps, e.g. ¼ inch, will accommodate the swelling

# *Thermal Expansion*

PVC Thermal expansion:
For a 10C temperature change, we get 0.67 mil/inch
This is additive/ subtractive to 2 to 4 mil swelling from oil pressure –argues for smaller block sizes

Top will simply grow/shrink in beam direction:
1.2 inches total (+- 0.6 inch); 0.9 mrad slant at each end
Negligible stress from this deformation.

Oil Thermal Expansion:
Linear CTE = 1.92e-3 per C (minus 6.7 e-5 for the PVC)
Take 53 ft high x 10 C gives height change = 12 inches
Must leave room for this oil.
Does not contribute to PVC stresses at all.

# *Stress in Extrusions next to Gap*

One side of each gap will have a vertical extrusion that is exposed, i.e. not glued to a horizontal one.

We know that a minimum of 30% glue coverage is needed to hold stresses to about 1 ksi

The “exposed” extrusions can be made with a special die, with wall thickness of 4mm rather than the normal 3mm. For 16-plane blocks, one in eight extrusions would have 4 mm walls.

# *Gluing the Tops of the Blocks together, using a Spacer Board*

When a block is complete, and one wants to start assembling the next block, room must be set aside for the block's swelling when it is filled with oil (the dry stack has no swelling).

At the bottom this can be achieved by inserting a spacer strip.

At the top it is desirable to create a firm connection between successive blocks. The connection can be made by gluing a ¼ inch spacer board, about a foot high, all the way across across, to the top of the extrusions.

# *Floor and Grouting*

The force for one vertical  extrusion base plate is 1946 kg, close to two tons.

The base plate will need to be supported over its whole are or it can crack.

We will spread  a grout (e.g. plaster of Paris or mortar mix) on the floor area before setting each block.

# Oil Containment

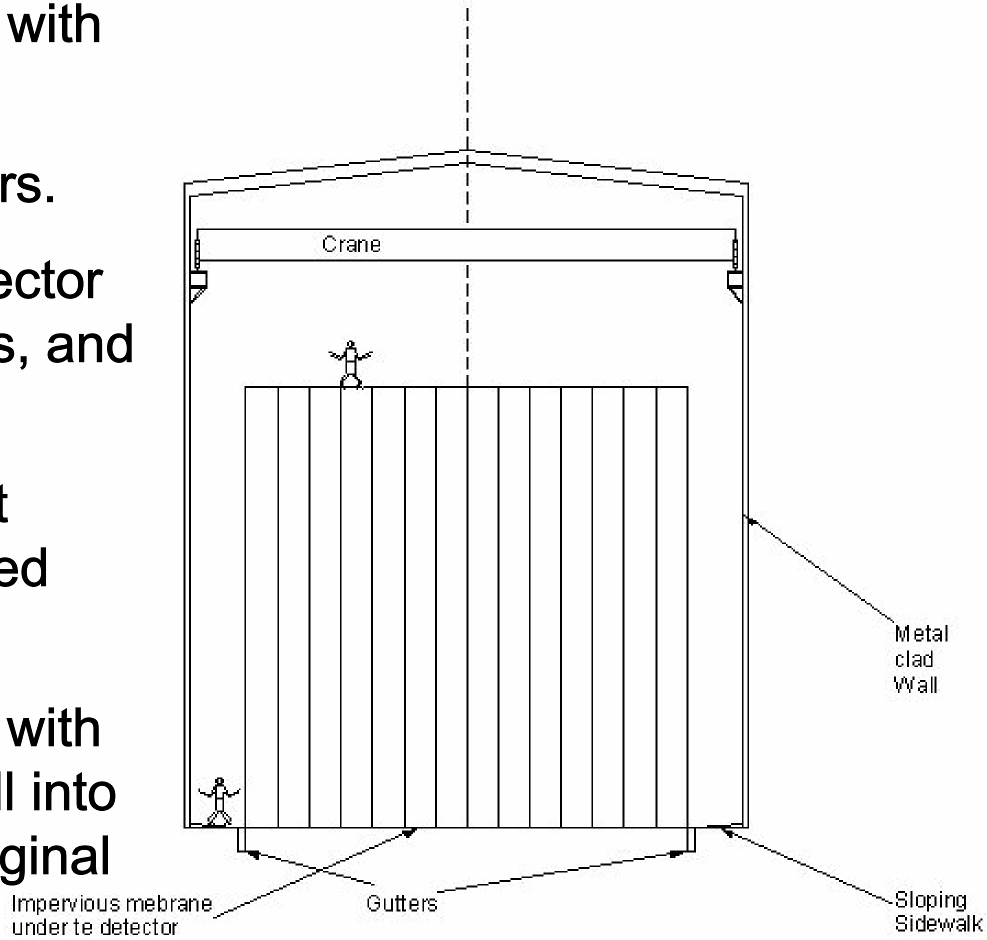
Install gutters  in the floor on both sides of the  to detector, covered with grating.

Sidewalks slope toward the gutters.

Leaking oil anywhere in the detector exits at the base or over the sides, and collects in the gutters.

The interior building wall is sheet metal clad to deflect any oil ejected through side walls.

The gutters slope toward sumps with ejector pumps to transfer any spill into a waste tank. (we can use the original filling tanks as waste tanks)




Oil Containment for the NOVA Detector

Hans Jostlein 1

# *Assembling a Totally Active Scintillation Detector*

The detector has 1845 planes. To assemble the whole detector in 3 years one must assemble 3 planes a day. The epoxy will take several hours to cure sufficiently for handling.

Installing extrusions individually means handling awkwardly large yet flexible objects of significant weight (149 kg ) at various elevations between ground level and 57 ft off the ground. This will require fairly elaborate lifting and fixturing equipment.

The readout electronics needs to be installed, from the snouts to the final readout fiber. This involves installation and testing work at all elevations.

# *A Proposal for Assembly*

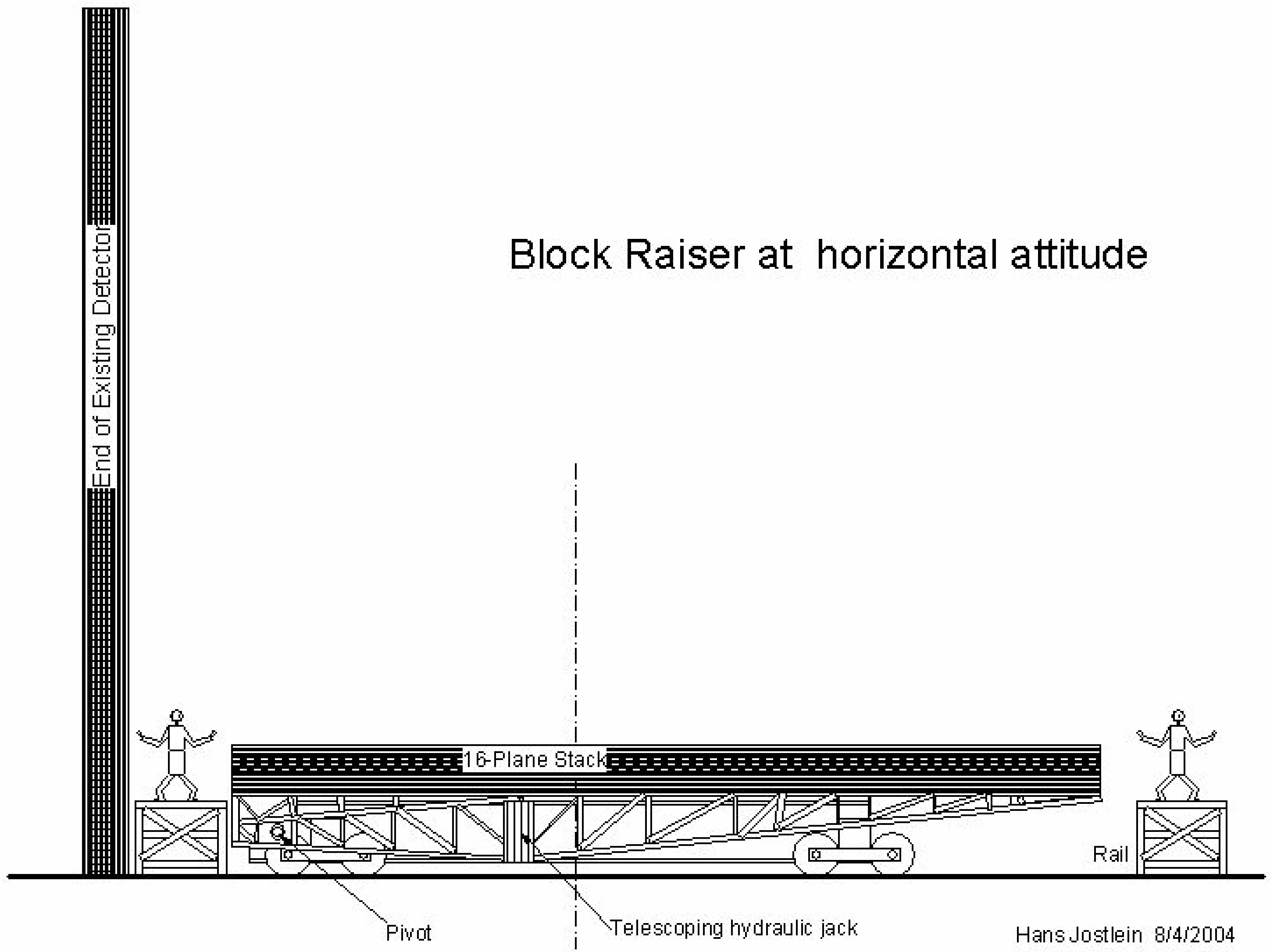
We propose to assemble 16 detector planes at a time, called a “block”.
The assembly is made on a horizontal table.
Advantages:
--the work occurs near ground level
--extrusions can just be laid down for gluing
--gluing pressure can be applied simply by weights
--electronics can be connected and tested at ground level.
--we can assemble planes much faster than the minimum of three per day mentioned above. A rate as high as one 16-plane blocks every other day may be attainable, which would complete the detector in 230 working days. This can cut costs and bring the detector on-line more quickly.

# *The Block Raiser*

The Block Raiser is a large assembly table that can be tilted to the vertical hydraulically.
It rides on railcar wheels on two standard railway rails that run for the full length of the detector hall.
The total weight is 34 tons for an empty block plus 61 tons for the Block Raiser itself.
It provides the holding force on the plane during gluing.
It controls spacing to assure precise assembly.

The decking is shimmed rather carefully to provide a flat surface for construction of the planes. The edge that becomes the bottom when the table is tilted has a series of forklift-type forks that prevent the block from sliding when the table is tilted up.

# Sketch of the Block Raiser



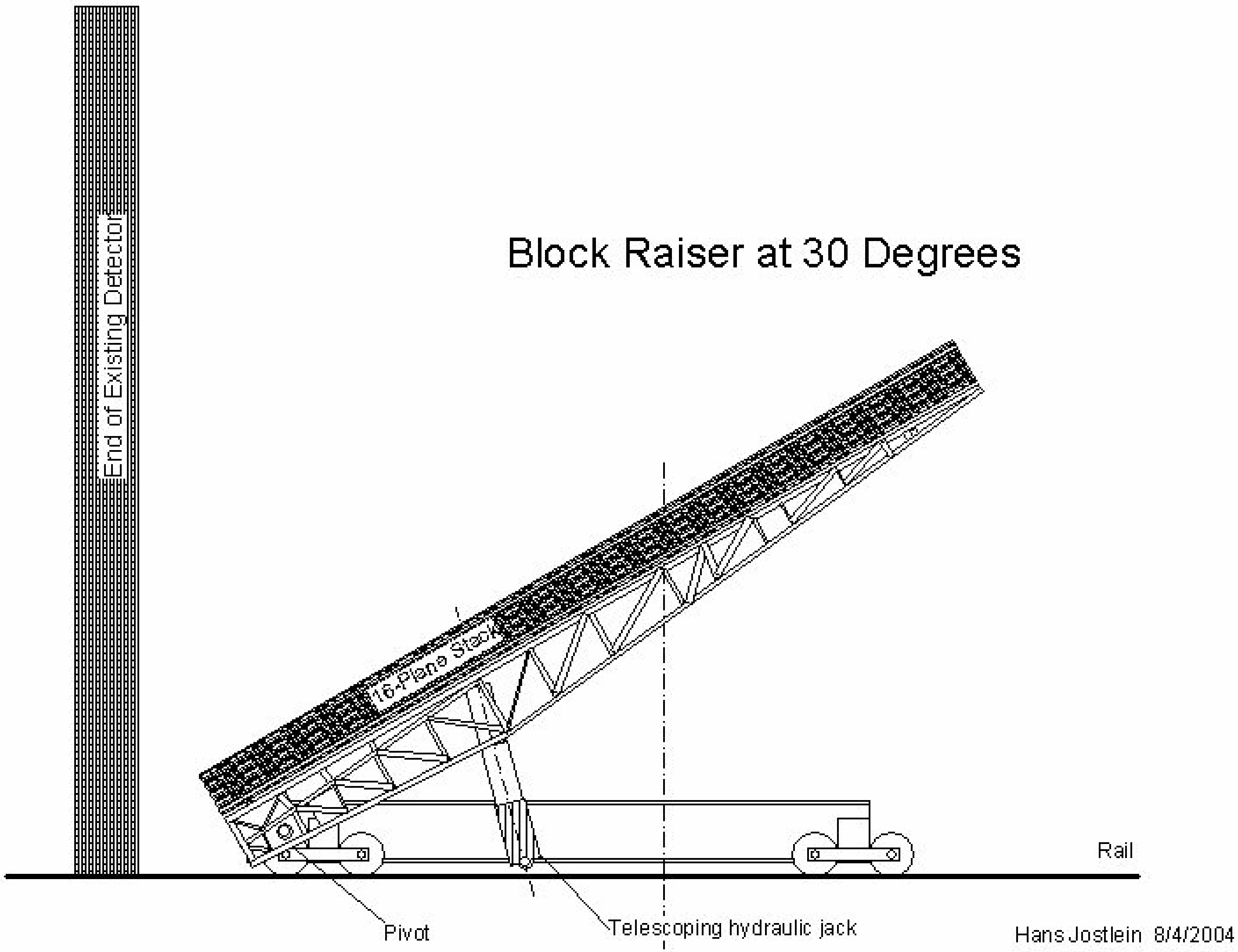
# *The Deck of the Block Raiser*

<u>The deck also has a special features:</u>
it can hold extrusions and completed blocks toward the decking with vacuum applied through a number of pipe connections through the decking.

A vacuum of just 0.14 psi can hold the weight of a completed 16-layer block.

The table is tilted by two telescoping hydraulic cylinders. When the center of gravity of the tilt table and block passes over the hinge point, a second pair of (smaller) cylinders is used to control the forward motion of the load.

# Another Picture of the Block Raiser



# *The Simple Table*

The work flow is helped by a second assembly table, the "Simple Table".

This table is of the same size, i.e. 17.5 m x 17.5 m, and of the same height as the Block Raiser table is when in the horizontal attitude. It is also supported by railroad wheels.

The Simple Table is equipped with a vacuum pipe system and an inflatable edge seal, just like the Block Raiser table.

Completed blocks are transferred from the simple table to the block raiser by putting positive pressure into the pipe system to float the block.

# What is the Right Block Length ?

Longer blocks lengths are more stable. However, when the block tops are connected to each other, we have mechanically essentially the same structure as if the detector was all one large stack.

Shorter stacks will have less aggregate swelling and less deformation near the bottoms.

If the detector is assembled from Blocks constructed on the floor and raised up, these blocks may be of a natural size to assemble the detector from.

The number of planes in a block may, in turn be governed by convenient interconnect numbers.

Stacks of 16 planes, weighing 34 tons, may be reasonable. In this case, each gap would be about 2 mm wide.

Buckling stability and construction safety will be assured by gluing each block at the top to the existing structure.

# *Summary and Conclusions*

The TASD detector for NOVA is an unusually large PVC structure. It has been modeled in finite element analyses in great detail.

<u>We have learned that:</u>

--the structure can be built within conservative stress limits in the PVC

--adequate safety factors can be provided

--the web-tearing failure mode in bad extrusions needs more study

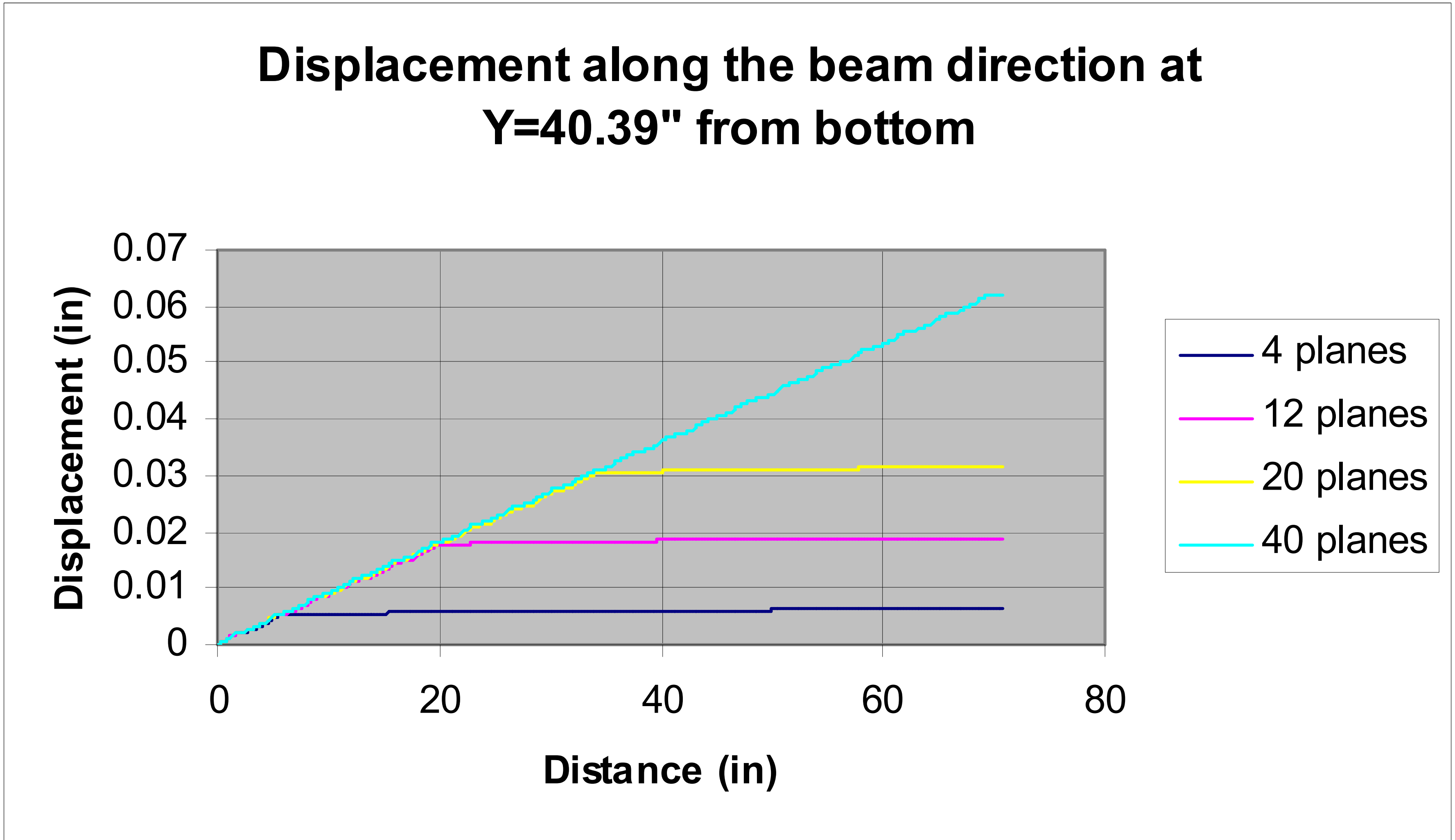
--small periodic expansion gaps must be reserved to allow for swelling when oil is filled into the cells

--planes should be connected at their tops for construction safety

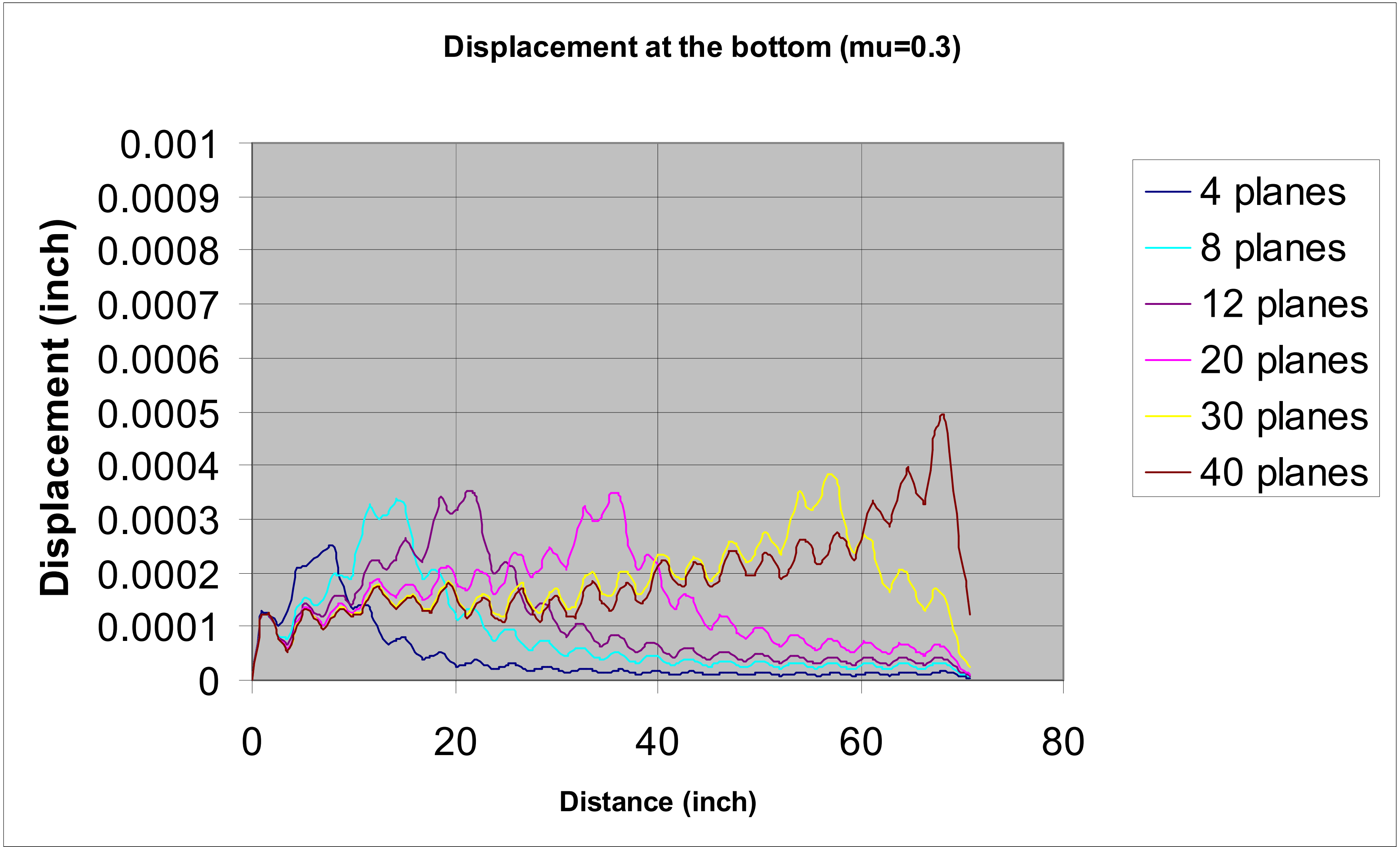
--construction can easily meet schedule requirements

# Background Slides

# Displacement at 40 “ from the bottom



# Displacement at the bottom during stepwise filling



# *The Oil Filling Challenge*

We’ll need to fill 7 tons of oil per hour into extrusions.

The task can be done using portable automated filling machines that fill several extrusions at once .

If a single worker does the whole job.

# *Oil Filling Concept*

NOVA – TASD is made up of 28,000 extrusions / modules.
Each holds 823 kg of oil, for a total oil mass of 23 kton.

We want to fill all extrusions with oil in 400 shifts

Fill rate is 57,600 kg per shift,

7.2 tons per hour, or 120 kg per minute, or 40 gal per minute.

# *Constraints*

We must fill to the exact level

We must not overfill or spill

We should fill slowly to minimize entrained air and bubbles

We must fill slowly  to allow the oil to flow across the passage holes between extrusion channels

# *Fill Rate*

Assume a fill rate of 1 kg per minute
(ANL is performing tests on acceptable fill rates, and we may have to adjust this number later.)

At this rate, we must fill 120 extrusions simultaneously.

Counting time for setups ( 25% ) we'll need to have the capacity to fill 150 extrusions simultaneously.

Clearly some degree of automation is needed.

# *Snouts with Fill Tubes*

Run two plastic tubes from each extrusion snout to a common panel that may serve one or two planes (14 or 28 extrusions)

The panels are simply plates with holes to hold the hose ends.

They will have labels and barcodes at each hose location.

One of the tubes is ½ inch diameter and is the oil fill line;

The other tube is ¼ inch diameter and connects to a dip tube in the snout.

# *The Cow*

The filling machine (“The Cow” ) is a suitcase-sized box that receives oil from a pipe line and fills 14 extrusions simultaneously.

The cow has a bar code reader to track the filling of each extrusion.

The cow connects to the fill tube and the dip tube of each extrusion.

The connection is made by inexpensive self-locking plastic fittings.

# *Cow Innards*

During normal filling, oil enters the fill tube, and air returns from the dip tube.
The air flow is sensed by the filling machine .
Once the oil reaches the bottom of the dip tube, the return air flow stops, and the cow stops delivering oil.

The cow also meters the oil to 1% accuracy and shuts off if the oil mass exceeds the expected amount.

If the air flow stops too early, that also raises an alarm.

Finally, the cow saves all filling data, and can transmit them through WiFi in real time, for monitoring.

# *How many Cows?*

We'll need  11 cows, plus spares, to fill the whole detector in 400 shifts.

Each cow cycle takes 823 minutes or 14 hours.

If a single worker does the whole job,
this leaves a little over an hour available, per cow, for change-over.

The total manpower would, then, be 400 shifts, or 2 FTE years for the filling operation.

# The Vee Alternative

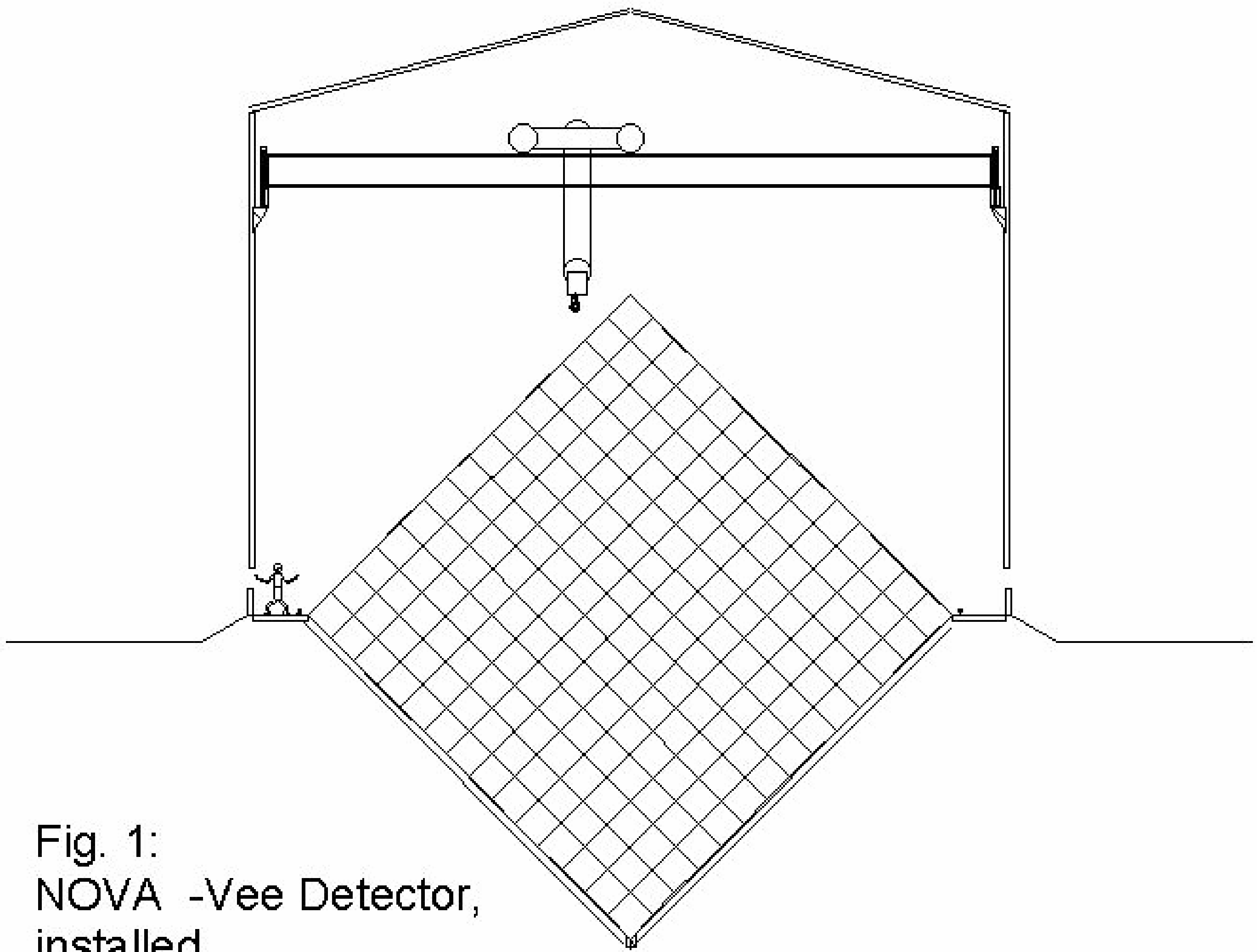



Fig. 1:
NOVA -Vee Detector,
installed

# The Vee Alternative

Some advantages accrue:

--the hydrostatic pressure is lower by sqrt(2), i.e. 15 psi rather than 21 psi. This may allow thinner wall extrusions

--there will be no major air bubbles in the oil.

--if the floor is excavated to make room for the Vee, less shielding would be needed if an overburden is required

--if the Vee is excavated, the building becomes less tall
--secondary oil containment may get easier

# The Vee Alternative

Some disadvantages :

--there is no level floor for workers to stand on; rolling scaffolding is needed

--it is harder to design a “block raiser” type installing machine

--the hall becomes wider

--there is some hall excavation

--There is no level deck on top; gangways would need to be added for working on top of the detector

# *Air Bubbles in Oil*

Due to filling turbulence, trapped volumes, or outgassing, air bubbles may exist in the horizontal extrusions and not clear themselves over time. This is being studied at ANL.

Possible remedies include:

--fill procedures that use laminar flow
--tilting the horizontal extrusions a little
--pulling a temporary vacuum on the tubes after filling, to increase bubble size and make them move out

# A special Epoxy for PVC

Strong; no volatile components; tixotropic

| Property | Magnolia 59-7 |
|---|---|
| | |
| Cure Schedule | Set – 24 hours or 2 hours @ 135°F; Adhesion – 3 days; Full Cure – 7 days |
| Mix Ratio – Parts By Weight (Part A:Part B) | 100:39 |
| Shelf Life | A: 6 months B: 6 months |
| Specific Gravity | Part A: 1.30<br>Part B: 1.40<br>Mix: 1.35 |
| Viscosity @ 77°F | Part A: Semi-paste<br>Part B: Semi-paste<br>Mix: Semi-paste |
| SPI Classification | A: 2 B: 4 |
| Color | A: White B: Black |